

MEASURE THEORETICAL ENTROPY OF COVERS

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ABSTRACT. In this paper we introduce three notions of measure theoretical entropy of a measurable cover \mathcal{U} in a measure theoretical dynamical system. Two of them were already introduced in [R] and the new one is defined only in the ergodic case. We then prove that these three notions coincide, thus answering a question posed in [R] and recover a variational inequality (proved in [GW]) and a proof of the classical variational principle based on a comparison between the entropies of covers and partitions.

1. INTRODUCTION

In this paper a measure theoretical dynamical system (m.t.d.s) is a four tuple (X, \mathcal{B}, μ, T) , where (X, \mathcal{B}) is a standard space (i.e isomorphic to $[0, 1]$ with the Borel σ -algebra), μ is a probability measure on (X, \mathcal{B}) and T is an invertible measure preserving map from X to itself.

A topological dynamical system (t.d.s) is a pair (X, T) , where X is a compact metric space and T is a homeomorphism from X to itself.

In [R] the author introduced two notions of measure theoretical entropy of a cover, both generalizing the definition of measure theoretical entropy of a partition and influenced by [BGH]. Namely,

- (1) $h_\mu^+(\mathcal{U}) = \inf_{\alpha \succeq \mathcal{U}} h_\mu(\alpha)$
- (2) $h_\mu^-(\mathcal{U}) = \lim_{n \rightarrow \infty} \inf_{\alpha \succeq \mathcal{U}_0^{n-1}} H_\mu(\alpha)$

It was shown there among other things that $h_\mu^-(\mathcal{U}) \leq h_\mu^+(\mathcal{U})$ and that in the topological case (i.e a t.d.s and an open cover), one can always find an invariant measure μ such that $h_\mu^-(\mathcal{U}) = h_{top}(\mathcal{U})$. This generalizes the result from [BGH] asserting that in the topological case one can always find an invariant measure μ such that $h_\mu^+(\mathcal{U}) \geq h_{top}(\mathcal{U})$.

The question whether $h_\mu^-(\mathcal{U}) = h_\mu^+(\mathcal{U})$ arose. In [HMRY] the authors continued the research on these concepts and proved, among other results, with aid of the Jewett-Krieger theorem, that if there exists a t.d.s, an invariant measure μ and an open cover \mathcal{U} such that $h_\mu^-(\mathcal{U}) < h_\mu^+(\mathcal{U})$ then one can find such a situation in a uniquely ergodic t.d.s. Recently, B.Weiss and E.Glasner [GW] showed that if (X, T) is a t.d.s and \mathcal{U} is any cover, then for any invariant measure μ $h_\mu^+(\mathcal{U}) \leq h_{top}(\mathcal{U})$ and so combining these results one concludes that for a t.d.s and an open cover we have that $h_\mu^-(\mathcal{U}) = h_\mu^+(\mathcal{U})$.

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The measure theoretical entropy of a partition α in an ergodic m.t.d.s can be defined as: $\lim \frac{1}{n} \log \mathcal{N}(\alpha_0^{n-1}, \epsilon)$, where $0 < \epsilon < 1$ and $\mathcal{N}(\alpha_0^{n-1}, \epsilon)$ is the minimum number of atoms of α_0^{n-1} needed to cover X up to a set of measure, less than ϵ . (See [Ru]).

In this paper we follow this line and in section 4 define a notion of measure theoretical entropy for a cover \mathcal{U} of an ergodic m.t.d.s as $h_\mu^e(\mathcal{U}) = \lim \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon)$ (where $0 < \epsilon < 1$). We prove (Theorem 4.2) the existence of the limit and its Independence of ϵ , in a different way from [Ru] using Strong Rohlin Towers. This can serve as an alternative proof of the fact that the above definition of measure theoretical entropy of a partition in an ergodic m.t.d.s is well defined.

We show in a direct way that in the ergodic case the three notions: $h_\mu^-(\mathcal{U}), h_\mu^+(\mathcal{U}), h_\mu^e(\mathcal{U})$, coincide (Theorems 4.4, 4.5), and from the ergodic decomposition for $h_\mu^-(\mathcal{U}), h_\mu^+(\mathcal{U})$, proved in [HMRY], we deduce that $h_\mu^-(\mathcal{U}) = h_\mu^+(\mathcal{U})$ in the general case (Corollary 5.2), and so, we can denote this number by $h_\mu(\mathcal{U}, T)$ or $h_\mu(\mathcal{U})$.

We also get an immediate proof of a slight generalization of the inequality $h_\mu(\mathcal{U}) \leq h_{top}(\mathcal{U})$, mentioned earlier, from [GW], to the non topological case (Theorem 6.1).

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2. PRELIMINARIES

Recall that in the following a measure theoretical dynamical system, (m.t.d.s), is a four tuple (X, \mathcal{B}, μ, T) , where (X, \mathcal{B}) is a standard space, μ is a probability measure on (X, \mathcal{B}) and T is an invertible measure preserving transformation of X .

2.1. Definition.

- A cover of X is a finite collection of measurable sets that cover X .
- The collection of covers of X will be denoted by \mathcal{C}_X
- A partition of X is a cover of X whose elements are mutually disjoint.
- The collection of partitions of X will be denoted by \mathcal{P}_X .
- Usually we denote covers by \mathcal{U}, \mathcal{V} and partitions by α, β, γ etc.
- We say that a cover \mathcal{U} is finer than \mathcal{V} ($\mathcal{U} \succeq \mathcal{V}$) if any element of \mathcal{U} is contained in an element of \mathcal{V} .
- For any $\mathcal{U} \in \mathcal{C}_X$ and $k \in \mathbb{Z}$ we denote by $T^k(\mathcal{U})$ the cover whose elements are the sets of the form $T^k(U)$ where $U \in \mathcal{U}$.
- We define the join, $\mathcal{U} \vee \mathcal{V}$, of two covers \mathcal{U}, \mathcal{V} , to be the cover whose elements are sets of the form $U \cap V$ where $U \in \mathcal{U}$ and $V \in \mathcal{V}$.
- When the transformation T is understood we denote, for $l > k$, the cover $T^{-k}(\mathcal{U}) \vee T^{-(k+1)}(\mathcal{U}) \cdots \vee T^{-l}(\mathcal{U})$, by \mathcal{U}_k^l .

2.2. Definition. For $0 < \delta < 1$ define $H(\delta) = -\delta \log \delta - (1 - \delta) \log(1 - \delta)$. Note that $\lim_{\delta \rightarrow 0} H(\delta) = 0$.

In the sequel, we will prove some combinatorial lemmas and often we will encounter the expression $\sum_{j \leq \delta K} \binom{K}{j}$. We shall make use of the next elementary lemma:

2.3. Lemma. (lemma 1.5.4 in [Sh1]): If $\delta < \frac{1}{2}$ then $\sum_{j \leq \delta K} \binom{K}{j} \leq 2^{H(\delta)}$.

2.4. Definition. A m.t.d.s (X, \mathcal{B}, μ, T) is said to be aperiodic, if for every $n \in \mathbb{N}$, $\mu(\{x | T^n x = x\}) = 0$.

An ergodic system which is not aperiodic is easily seen to be a cyclic permutation on a finite number of atoms.

One of our main tools in practice, will be the Strong Rohlin Lemma ([Sh2] p.15):

2.5. Lemma. Let (X, \mathcal{B}, μ, T) be an ergodic, aperiodic system and let $\alpha \in \mathcal{P}_X$. Then for any $\delta > 0$ and $n \in \mathbb{N}$, one can find a set $B \in \mathcal{B}$, such that $B, TB, \dots, T^{n-1}B$ are mutually disjoint, $\mu(\bigcup_0^{n-1} T^i B) > 1 - \delta$ and the distribution of α is the same as the distribution of the partition $\alpha|_B$ that α induces on B .

The data (n, δ, B, α) will be called, a strong Rohlin tower of height n and error δ with respect to α and with B as a base.

3. MEASURE THEORETICAL ENTROPY OF COVERS

Let (X, \mathcal{B}, μ, T) be a m.t.d.s. The definitions and proofs in this section were introduced in [R].

3.1. Definition. for $\mathcal{U} \in \mathcal{C}_X$ we define the entropy of \mathcal{U} as:

$$H_\mu(\mathcal{U}) = \inf_{\alpha \succeq \mathcal{U}} H_\mu(\alpha).$$

3.2. Proposition.

- (1) If $\mathcal{U}, \mathcal{V} \in \mathcal{C}_X$ then $H_\mu(\mathcal{U} \vee \mathcal{V}) \leq H_\mu(\mathcal{U}) + H_\mu(\mathcal{V})$.
- (2) For every $\mathcal{U} \in \mathcal{C}_X$ $H_\mu(T^{-1}\mathcal{U}) = H_\mu(\mathcal{U})$

3.3. Corollary. If $\mathcal{U} \in \mathcal{C}_X$ then the sequence $H_\mu(\mathcal{U}_0^{n-1})$ is sub-additive.

3.4. Corollary. If $\mathcal{U} \in \mathcal{C}_X$ then the sequence $\frac{1}{n} H_\mu(\mathcal{U}_0^{n-1})$ converges to $\inf_n \frac{1}{n} H_\mu(\mathcal{U}_0^{n-1})$.

Two ways of generalizing the definition of measure theoretical entropy of a partition to a cover are:

3.5. Definition. If $\mathcal{U} \in \mathcal{C}_X$, define

- (1) $h_\mu^-(\mathcal{U}, T) = \lim_{n \rightarrow \infty} \frac{1}{n} H_\mu(\mathcal{U}_0^{n-1})$.
- (2) $h_\mu^+(\mathcal{U}, T) = \inf_{\alpha \succeq \mathcal{U}} h_\mu(\alpha, T)$.

When T is understood we usually omit it and write $h_\mu^-(\mathcal{U})$, $h_\mu^+(\mathcal{U})$.

We shall see later that in fact $h_\mu^-(\mathcal{U}) = h_\mu^+(\mathcal{U})$.

3.6. Proposition.

- (1) $h_\mu^-(\mathcal{U}) \leq h_\mu^+(\mathcal{U})$.
- (2) for any $m \in \mathbb{N}$ $h_\mu^-(\mathcal{U}, T) = \frac{1}{m} h_\mu^-(\mathcal{U}_0^{m-1}, T^m)$
- (3) $h_\mu^-(\mathcal{U}, T) = \lim_n \frac{1}{n} h_\mu^+(\mathcal{U}_0^{n-1}, T^n)$

4. THE ERGODIC CASE

Throughout this section, (X, \mathcal{B}, μ, T) , is an ergodic m.t.d.s.

For $\mathcal{U} \in \mathcal{C}_X$, we denote by $\mathcal{N}(\mathcal{U}, \epsilon, \mu)$, the minimum number of elements of \mathcal{U} , needed to cover all of X , up to a set of measure, less than ϵ . When μ is understood we write $\mathcal{N}(\mathcal{U}, \epsilon)$.

By a strait forward calculation one deduces from [Sh1] p.51 the following:

4.1. Theorem. *If (X, \mathcal{B}, μ, T) is an ergodic m.t.d.s and $\alpha \in \mathcal{P}_X$, then for any $0 < \epsilon < 1$, $h_\mu(\alpha, T) = \lim \frac{1}{n} \log \mathcal{N}(\alpha_0^{n-1}, \epsilon)$.*

In view of this result, a natural way to generalize the definition of measure theoretical entropy of a partition to covers will be the following:

$$h_\mu(\mathcal{U}, T) = \lim \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon).$$

Where $0 < \epsilon < 1$. In order to do so we have to show that the above limit exists and is independent of ϵ .

4.2. Theorem. *For any $0 < \epsilon < 1$, the sequence $\frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon)$ converges and the limit is independent of ϵ .*

In order to prove this theorem we shall need a combinatorial lemma. Let us first introduce some terminology (in first reading the reader may skip the following discussion and turn to the discussion held after the proof of Lemma 4.3):

- We say that two intervals in \mathbb{N} , I, J are separated if there is $n \in \mathbb{N}$ such that for any $i \in I, j \in J$ we have $i < n < j$ or $j < n < i$.
- We say that a collection $\{I_i\}_{i \in A}$ of intervals in \mathbb{N} is a separated collection if any two of its elements are separated.
- We say that a collection $\{I_i\}_{i \in A}$ of subintervals of an interval $[1, K]$ is a (λ, ϵ) separated cover of $[1, K]$ (for $0 < \lambda < 1, 0 < \epsilon$), if it is separated and

$$\left| \frac{|\cup I_i|}{K} - \lambda \right| < \epsilon.$$

- Given a vector $\vec{\lambda} = (\lambda_1 \dots \lambda_l)$, we denote

$$\nu_r(\vec{\lambda}) = \prod_{j=r}^l (1 - \lambda_j)$$

or just ν_r when $\vec{\lambda}$ is understood. For $r > l$ we set $\nu_r = 1$. Note that for $j < l$ we have:

$$\sum_{r=j+1}^l \lambda_r \nu_{r+1} = 1 - \nu_j.$$

In the following combinatorial lemma, we will be given l separated collections $\{I_i^j\}_{i \in A_j}$, $j = 1 \dots l$ of subintervals of a very long interval $[1, K]$. The knowledge about these collections is that the members of the j 'th collection all have the same length, N_j , $N_1 << N_2 \dots << N_l$ and every collection is very "equally distributed" in $[1, K]$ in some sense. We would like to extract, from these collections, a separated collection that will cover as much as we can, from $[1, K]$.

Let us denote by λ_j , the percentage of $[1, K]$, that is covered by the j 'th collection and by $\vec{\lambda}$, the corresponding vector. Then, $\lambda_l = 1 - \nu_l$ percent of $[1, K]$ is covered by $\{I_i^l\}$. The complement is of size $K\nu_l$ and we could cover λ_{l-1} percent of it with the $\{I_i^{l-1}\}$'s. By now we covered $K(1 - \nu_{l-1})$ and we could cover λ_{l-2} percent of the complement by the $\{I_i^{l-2}\}$'s. So by now we covered $K(1 - \nu_{l-2})$ of $[1, K]$. We go on this way and extract a separated collection that covers $1 - \nu_1$ percent of $[1, K]$. Let us now make these ideas precise.

4.3. Lemma. *For any $l > 0$, there exists a positive function $\varphi = \varphi(N_1 \dots N_l, \eta_1 \dots \eta_l, \epsilon)$ (where $N_1 < N_2 \dots < N_l \in \mathbb{N}$, $\eta_i, \epsilon > 0$) such that*

$$\limsup_{\epsilon \rightarrow 0} \limsup_{N_1 \rightarrow \infty} \limsup_{\eta_1 \rightarrow 0} \dots \limsup_{N_l \rightarrow \infty} \limsup_{\eta_l \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) = 0. \quad (*)$$

and such that if $0 < \lambda_j < 1$ $j = 1 \dots l$ and $\{I_i^j\}_{i \in A_j}$ are separated collections of subintervals of $[1, K]$ that satisfy:

- (a) For every $1 \leq j \leq l$ $|I_i^j| = N_j$.
- (b) For every $1 \leq j \leq l$ $\{I_i^j\}$ is a (λ_j, ϵ) -separated cover of $[1, K]$.
- (c) For every $0 \leq j < r \leq l$, the number of subintervals, J , of $[1, K]$, of length N_r , which are not (λ_j, ϵ) -separately covered by $\{I_i^j \subset J\}$ is less than $\eta_r K$.

then there are sets $\tilde{A}_j \subset A_j$ $j = 1 \dots l$, such that $\{\{I_i^j\}_{i \in \tilde{A}_j}\}_{j=1}^l$ is a separated collection and $[1, K]$ is $((1 - \nu_1(\vec{\lambda})), \varphi(N_i, \eta_i, \epsilon))$ -separately covered by $\{\{I_i^j\}_{i \in \tilde{A}_j}\}_{j=1}^l$.

Proof. We will build the \tilde{A}_j 's by recursion, starting with $j = l$. Define $\tilde{A}_l = A_l$. Then from (b) we have that $|\frac{N_l |\tilde{A}_l|}{K} - \lambda_l| < \epsilon$. So if we will define $f_l(N_i, \eta_i, \epsilon) = \epsilon$, then f_l satisfies (*) and $[1, K]$ is $(\lambda_l \nu_{l+1}, f_l(N_i, \eta_i, \epsilon))$ -separately covered by $\{I_i^l\}_{i \in \tilde{A}_l}$. Now, suppose we have defined $\tilde{A}_l \dots \tilde{A}_{j+1}$ and positive functions $f_l \dots f_{j+1}$, that satisfy (*), such that $\{\{I_i^r\}_{i \in \tilde{A}_r}\}_{r=j+1}^l$ is a separated collection and for every $j+1 \leq r \leq l$, $[1, K]$ is $(\lambda_r \nu_{r+1}, f_r(N_i, \eta_i, \epsilon))$ -separately covered by $\{I_i^r\}_{i \in \tilde{A}_r}$. Define now,

$$\tilde{A}_j = \{i \in A_j \mid I_i^j \text{ is separated from } \{I_s^r\}_{s \in \tilde{A}_r}, r = j+1 \dots l\}.$$

We want to estimate the size of \tilde{A}_j .

Estimation from below: Choose $j+1 \leq r \leq l$ and divide the members of $\{I_i^r\}_{i \in \tilde{A}_r}$ to good ones and bad ones according to (c), i.e., I_s^r is good if it is (λ_j, ϵ) -separately covered by $\{I_i^j \subset I_s^r\}$. We have at most $\eta_r K$, I_i^r 's, which are bad and at most $|\tilde{A}_r|$, I_i^r 's, which are good. Every bad I_i^r rules out at most $\frac{N_r}{N_j} + 2$ i 's in A_j from being in \tilde{A}_j . Every good I_i^r rules out at most $\frac{N_r}{N_j}(\lambda_j + \epsilon) + 2$, i 's in A_j from being in \tilde{A}_j . In total, the maximum number of i 's in A_j that are not in \tilde{A}_j is at most:

$$\sum_{r=j+1}^l |\tilde{A}_r| \left(\frac{N_r}{N_j}(\lambda_j + \epsilon) + 2 \right) + \eta_r K \left(\frac{N_r}{N_j} + 2 \right) = (**)$$

Note that because $[1, K]$ is $(\lambda_r \nu_{r+1}, f_r)$ -separately covered by $\{I_i^r\}_{i \in \tilde{A}_r}$, we must have

$$|\tilde{A}_r| \leq \frac{K}{N_r} (\lambda_r \nu_{r+1} + f_r).$$

Using this we get:

$$\begin{aligned} (**) &\leq \sum_{r=j+1}^l \frac{K}{N_r} (\lambda_r \nu_{r+1} + f_r) \left(\frac{N_r}{N_j}(\lambda_j + \epsilon) + 2 \right) + \eta_r K \left(\frac{N_r}{N_j} + 2 \right) \\ &= \sum_{r=j+1}^l \frac{K}{N_j} \lambda_r \nu_{r+1} (\lambda_j + \epsilon) + \frac{K}{N_j} (\lambda_j + \epsilon) f_r + \frac{2K}{N_r} (\lambda_r \nu_{r+1} + f_r) + \frac{K}{N_j} \eta_r N_r + 2\eta_r K \\ &= \frac{K}{N_j} \lambda_j \left(\sum_{r=j+1}^l \lambda_r \nu_{r+1} \right) \\ &\quad + \frac{K}{N_j} \sum_{r=j+1}^l \left\{ \epsilon \lambda_r \nu_{r+1} + (\lambda_j + \epsilon) f_r + 2 \frac{N_j}{N_r} (\lambda_r \nu_{r+1} + f_r) + \eta_r (N_r + 2N_j) \right\} = (\aleph) \end{aligned}$$

as mentioned earlier $\sum_{j+1}^l \lambda_r \nu_{r+1} = 1 - \nu_j$ so we have that:

$$\begin{aligned} |\tilde{A}_j| &\geq |A_j| - (\aleph) \geq \frac{K}{N_j} (\lambda_j - \epsilon) - (\aleph) \\ &= \frac{K}{N_j} \left\{ \lambda_j \nu_j - \left\{ \epsilon + \sum_{r=j+1}^l \left\{ \epsilon \lambda_r \nu_{r+1} + (\lambda_j + \epsilon) f_r + 2 \frac{N_j}{N_r} (\lambda_r \nu_{r+1} + f_r) + \eta_r (N_r + 2N_j) \right\} \right\} \right\} \end{aligned}$$

note that

$$\begin{aligned} &|(\epsilon + \sum_{r=j+1}^l \left\{ \epsilon \lambda_r \nu_{r+1} + (\lambda_j + \epsilon) f_r + 2 \frac{N_j}{N_r} (\lambda_r \nu_{r+1} + f_r) + \eta_r (N_r + 2N_j) \right\})| \\ &\leq \epsilon + \sum_{r=j+1}^l \left\{ \epsilon + (1 + \epsilon) f_r + 2 \frac{N_j}{N_r} (1 + f_r) + \eta_r (N_r + 2N_j) \right\} \end{aligned}$$

so if we will denote the last expression by $\tilde{f}_j(N_i, \eta_i, \epsilon)$, then we see that \tilde{f}_j satisfies $(*)$ and $|\tilde{A}_j| \geq \frac{K}{N_j}(\lambda_j \nu_{j+1} - \tilde{f}_j)$.

Estimation from above: For every $j+1 \leq r \leq l$, we have that $|\tilde{A}_r| \geq \frac{K}{N_r}(\lambda_r \nu_{r+1} - f_r)$ and the number of bad I_i^r 's is at most $\eta_r K$, so we must have at least $\frac{K}{N_r}(\lambda_r \nu_{r+1} - f_r) - \eta_r K$ good I_i^r 's. Every good I_i^r , rules out at least $\frac{N_r}{N_j}(\lambda_j - \epsilon)$ i 's in A_j from being in \tilde{A}_j . So the number of i 's in A_j that are not in \tilde{A}_j is at least:

$$\sum_{r=j+1}^l \frac{N_r}{N_j}(\lambda_j - \epsilon) \left\{ \frac{K}{N_r}(\lambda_r \nu_{r+1} - f_r) - \eta_r K \right\}$$

and so

$$\begin{aligned} |\tilde{A}_j| &\leq |A_j| - \sum_{r=j+1}^l \frac{N_r}{N_j}(\lambda_j - \epsilon) \left\{ \frac{K}{N_r}(\lambda_r \nu_{r+1} - f_r) - \eta_r K \right\} \\ &\leq \frac{K}{N_j}(\lambda_j + \epsilon) - \sum_{r=j+1}^l \left\{ \frac{K}{N_j} \left(\lambda_j(\lambda_r \nu_{r+1} - f_r) - \epsilon(\lambda_r \nu_{r+1} - f_r) \right) - \frac{K}{N_j} \eta_r N_r (\lambda_j - \epsilon) \right\} \\ &= \frac{K}{N_j} \left\{ \lambda_j \left(1 - \sum_{r=j+1}^l \lambda_r \nu_{r+1} \right) + \epsilon + \sum_{r=j+1}^l \left(\lambda_j f_r + \epsilon(\lambda_r \nu_{r+1} - f_r) + \eta_r N_r (\lambda_j - \epsilon) \right) \right\} \\ &\leq \frac{K}{N_j} \left\{ \lambda_j \nu_{j+1} + \epsilon + \sum_{r=j+1}^l \left(f_r + \epsilon(1 + f_r) + \eta_r N_r (1 + \epsilon) \right) \right\} \end{aligned}$$

so if we will denote

$$\hat{f}_j(N_i, \eta_i, \epsilon) = \epsilon + \sum_{r=j+1}^l \left(f_r + \epsilon(1 + f_r) + \eta_r N_r (1 + \epsilon) \right)$$

then \hat{f}_j satisfies $(*)$ and $|\tilde{A}_j| \leq \frac{K}{N_j}(\lambda_j \nu_{j+1} + \hat{f}_j)$. Define $f_j = \max(\tilde{f}_j, \hat{f}_j)$ and then we have that f_j satisfies $(*)$ and

$$\left| \frac{|\tilde{A}_j| N_j}{K} - \lambda_j \nu_{j+1} \right| \leq f_j.$$

We have defined $\tilde{A}_j \subset A_j$ and a positive function f_j , that satisfies $(*)$, such that $\{\{I_i^r\}_{i \in \tilde{A}_r}\}_{r=j}^l$ is a separated collection and $[1, K]$ is $(\lambda_j \nu_{j+1}, f_j)$ -separately covered by $\{I_i^j\}_{i \in \tilde{A}_j}$.

We continue this way and define sets $\tilde{A}_j \subset A_j$ and positive functions f_j , $j = 1 \dots l$, such that $\{\{I_i^j\}_{i \in \tilde{A}_j}\}_{j=1}^l$, is a separated collection and $[1, K]$ is $(\lambda_j \nu_{j+1}, f_j)$ -separately covered by $\{I_i^j\}_{i \in \tilde{A}_j}$.

Note that this means:

$$K \left(\sum_{j=1}^l \lambda_j \nu_{j+1} - \sum_{j=1}^l f_j \right) \leq \left| \bigcup_{j=1}^l \bigcup_{i \in \tilde{A}_j} I_i^j \right| \leq K \left(\sum_{j=1}^l \lambda_j \nu_{j+1} + \sum_{j=1}^l f_j \right)$$

and so, if we will define $\varphi = \sum f_j$, then φ satisfies $(*)$ and $\{\{I_i^j\}_{i \in \tilde{A}_j}\}_{j=1}^l$, is a $(1 - \nu_1, \varphi)$ -separated cover of $[1, K]$. \square

Before turning to the proof of *theorem 4.2*, let us present some terminology. In the following $\mathcal{U} = \{U_1 \dots U_M\}$, is a cover of X . For any $\rho > 0$, we can find a partition $\beta \succeq \mathcal{U}$, such that $\mathcal{N}(\mathcal{U}, \rho) = \mathcal{N}(\beta, \rho)$. Namely, we choose a subset of \mathcal{U} , of $N = \mathcal{N}(\mathcal{U}, \rho)$ elements, that covers X up to a set of measure $< \rho$, $\{U_{i1} \dots U_{iN}\}$ and define $C_1 = U_{i1}$, $C_j = U_{ij} \setminus \bigcup_{m=1}^{j-1} U_{im}$, $j = 2 \dots N$. The C_j 's are disjoint, $C_j \subset U_{ij}$ and $\bigcup_1^N C_j = \bigcup_{j=1}^N U_{ij}$. Extend the collection $\{C_j\}_{j=1}^N$ to a partition, β , refining \mathcal{U} , in some way. Then, because $\beta \succeq \mathcal{U}$, we have $\mathcal{N}(\beta, \rho) \geq N$ and from our construction, it follows that $\mathcal{N}(\beta, \rho) \leq N$.

- We call such a partition, a ρ -good partition for \mathcal{U} .

If (X, \mathcal{B}, μ, T) is aperiodic and $N \in \mathbb{N}$, $\rho, \delta > 0$ are given, then for a ρ -good partition β , for \mathcal{U}_0^{N-1} , we can construct a strong Rohlin tower with height $N + 1$ and error $< \delta$. Let \tilde{B} denote the base of the tower and let $B \subset \tilde{B}$ be a union of $\mathcal{N}(\beta, \rho)$ atoms of $\beta|_{\tilde{B}}$ that covers \tilde{B} up to a set of measure, less than $\rho\mu(\tilde{B})$.

- We call (β, \tilde{B}, B) , a good base for $(\mathcal{U}, N, \rho, \delta)$.
- For a set $J \subset \mathbb{N}$, a (\mathcal{U}, J) -name, is a function $f : J \rightarrow \{1 \dots M\}$.
- f is a name of $x \in X$, if $x \in \bigcap_{j \in J} T^{-j} U_{f(j)}$.
- We denote the set of elements of X with f as a name by S_f .
- A set of (\mathcal{U}, J) -names, $\{f_i\}$, covers a set $C \in \mathcal{B}$, if $C \subset \bigcup_i S_{f_i}$.

In the sequel, we will want to estimate the number of elements of \mathcal{U}_0^{N-1} , needed to cover a set $C \in \mathcal{B}$, i.e, we will want to estimate the number of $(\mathcal{U}, [0, N - 1])$ -names needed to cover C . The usual way to do so is to find a collection of disjoint sets $J_i \subset [0, N - 1]$ $i = 1 \dots m$, that covers most of $[0, N - 1]$, such that we can bound the number of (\mathcal{U}, J_i) -names needed to cover C . If we can cover C by R_i , (\mathcal{U}, J_i) -names, $\{f_m^i\}_{m=1}^{R_i}$, then the set $\Gamma = \{f : [0, N - 1] \rightarrow \{1 \dots M\} \mid f|_{J_i} \in \{f_m^i\}_{m=1}^{R_i}\}$, of $(\mathcal{U}, [0, N - 1])$ -names, covers C and contains $\prod R_i \cdot M^{N - \sum |J_i|}$ elements.

This situation occurs in our proofs in the following way: Let (β, \tilde{B}, B) , be a good base for $(\mathcal{U}, N, \rho, \delta)$ and $K \gg N$. Set C to be the set of elements of X that visits B at times $i_1 < \dots < i_m$ between 0 to $K - N$ (under the action of T). Then we can cover C by no more than $\mathcal{N}(\beta, \rho)$, $(\mathcal{U}, [i_j, i_j + N - 1])$ -names. We can now turn to the proof of *theorem 4.2*.

Proof. (theorem 4.2): If (X, \mathcal{B}, μ, T) is periodic, it follows from the ergodicity, that the system is a cyclic permutation on a finite set of atoms and for every $0 < \epsilon < 1$ we have $\lim_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) = 0$. We assume, then, that the system is aperiodic and thus we are able to use the Strong Rohlin Lemma. Given $0 < \rho_2 < \rho_1 < 1$, we need to show that the limits: $\lim_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_i)$ $i = 1, 2$, exist and are equal. Note that for every n , we have that $\mathcal{N}(\mathcal{U}_0^{n-1}, \rho_1) \leq \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_2)$ and thus $\limsup_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_1) \leq \liminf_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_2)$, so it's enough to prove that

$$\limsup_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_2) \leq \liminf_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_1).$$

Let $0 < \epsilon_0 < \frac{1}{2}$, be given and denote:

$h_0 = \liminf \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_1)$, $L = \{n \in \mathbb{N} \mid |h_0 - \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \rho_1)| < \epsilon_0\}$,
so L contains arbitrarily large numbers. Choose $\ell \in \mathbb{N}$, large enough so that

$$\left(\frac{1}{2}(1 + \rho_1)\right)^\ell \log M < \epsilon_0, \quad \left(\frac{1}{2}(1 + \rho_1)\right)^\ell + \epsilon_0 < \frac{1}{2} \quad (*).$$

The towers construction: Remember the function φ from the combinatorial lemma (Lemma 4.3). It satisfies:

$$\limsup_{\epsilon \rightarrow 0} \limsup_{N_1 \rightarrow \infty} \limsup_{\eta_1 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) = 0$$

so we can choose $\epsilon > 0$, small enough, such that

$$\limsup_{N_1 \rightarrow \infty} \limsup_{\eta_1 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0.$$

Choose a small enough $\delta > 0$ (in a manner specified later). Choose $N_1 \in L$, large enough, such that

$$\limsup_{\eta_1 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0.$$

Find a good base $(\beta_1, \tilde{B}_1, B_1)$, for $(\mathcal{U}, N_1, \rho_1, \delta)$. Choose $\eta_1 > 0$, small enough, such that

$$\limsup_{N_2 \rightarrow \infty} \limsup_{\eta_2 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0.$$

From the ergodicity, we can choose $N_2 \in L$, large enough, such that

- $\limsup_{\eta_2 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0$.
- $\mu\{x \mid |\frac{1}{N_2} \sum_{r=0}^{N_2-N_1} \chi_{B_1}(T^r x) - \mu(B_1)| < \frac{\epsilon}{N_1}\} > 1 - \eta_1$.

Find a good base, $(\beta_2, \tilde{B}_2, B_2)$, for $(\mathcal{U}, N_2, \rho_1, \delta)$. Choose $\eta_2 > 0$, small enough, such that

$$\limsup_{N_3 \rightarrow \infty} \limsup_{\eta_3 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0.$$

Again, from the ergodicity, we can choose $N_3 \in L$, such that

- $\limsup_{\eta_3 \rightarrow 0} \dots \limsup_{N_\ell \rightarrow \infty} \limsup_{\eta_\ell \rightarrow 0} \varphi(N_i, \eta_i, \epsilon) < \epsilon_0$.
- $\mu\{x \mid |\frac{1}{N_3} \sum_{r=0}^{N_3-N_j} \chi_{B_j}(T^r x) - \mu(B_j)| < \frac{\epsilon}{N_j}, j = 1, 2\} > 1 - \eta_2$.

In this way we construct, inductively, $N_1 < N_2 \dots < N_\ell$ (all from L), $\eta_1 \dots \eta_\ell$ and good bases $(\beta_j, \tilde{B}_j, B_j)$, for $(\mathcal{U}, N_j, \rho_1, \delta)$, such that $\varphi(N_i, \eta_i, \epsilon) < \epsilon_0$ and if we denote

$$F_j = \{x \mid |\frac{1}{N_j} \sum_{r=0}^{N_j-N_i} \chi_{B_i}(T^r x) - \mu(B_i)| < \frac{\epsilon}{N_i}, i = 1 \dots j-1\}$$

then, $\mu(F_j) > 1 - \eta_j$.

Define

$$E_K = \{x \mid \frac{1}{K} \sum_{r=0}^{K-N_j} \chi_{F_j}(T^r x) > 1 - \eta_j, \mid \frac{1}{K} \sum_{r=0}^{K-N_j} \chi_{B_j}(T^r x) - \mu(B_j) \mid < \frac{\epsilon}{N_j}, j = 1 \dots \ell\}.$$

From the ergodicity, we know that there is a K_0 , such that, for any $K > K_0$, we have $\mu(E_K) > \rho_2$. Fix $K > K_0$, we shall show that we can cover E_K , by "few" $(\mathcal{U}, [0, K-1])$ -names. For a fixed $x \in E_K$ denote

$$A_j = \{0 \leq m \leq K - N_j \mid T^m x \in B_j\}$$

and for every $i \in A_j$, let $I_i^j = [i, i + N_j - 1]$. We claim that the collections $\{I_i^j\}_{i \in A_j}$, $j = 1 \dots \ell$, satisfies conditions (a), (b), (c) from the combinatorial lemma (lemma 4.3), with $\lambda_j = N_j \mu(B_j)$. To see this, note first, that because the height of the j 'th tower was $N_j + 1$, we have that each collection $\{I_i^j\}_{i \in A_j}$, is separated.

(a) By definition $|I_i^j| = N_j$.

(b) because $x \in E_k$, we know that $|\frac{1}{K} \sum_{r=0}^{K-N_j} \chi_{B_j}(T^r x) - \mu(B_j)| < \frac{\epsilon}{N_j}$ and thus, $|\frac{N_j |A_j|}{K} - \lambda_j| < \epsilon$. So the $\{I_i^j\}_{i \in A_j}$ forms a (λ_j, ϵ) -separated cover of $[0, K-1]$.

(c) For $1 < r \leq \ell$, we know from the fact that $x \in E_K$, that $\frac{1}{K} \sum_{s=0}^{K-N_r} \chi_{F_r}(T^s x) > 1 - \eta_r$ and thus we have $\frac{1}{K} \sum_{s=0}^{K-N_r} \chi_{F_r^c}(T^s x) < \eta_r$. If we use the definition of F_r , this becomes

$$\frac{1}{K} \# \{0 \leq s \leq K - N_r \mid \exists 1 \leq j \leq r-1 \mid \frac{1}{N_r} \sum_{i=0}^{N_r - N_j} \chi_{B_j}(T^{i+s} x) - \mu(B_j) \geq \frac{\epsilon}{N_j}\} < \eta_r$$

or equivalently

$$\#\{0 \leq s \leq K - N_r \mid \exists 1 \leq j \leq r-1 \mid \frac{N_j}{N_r} \# \{i \mid i + s \in A_j\} - \lambda_j \geq \epsilon\} < \eta_r K$$

so if we choose $1 \leq j < r \leq \ell$, we must have

$$\#\{J \subset [0, K-1] \mid |J| = N_r, \mid \frac{N_j}{N_r} \# \{i \mid I_i^j \subset J\} - \lambda_j \mid \geq \epsilon\} < \eta_r K.$$

In words, the number of subintervals of $[0, K-1]$ of length N_r , J , which are not (λ_j, ϵ) -separately covered, by those I_i^j which are contained in J is less than $\eta_r K$, as we wanted. Using the combinatorial lemma, we can choose for every $x \in E_K$ a separated collection $\{\{I_i^j(x)\}_{i \in \tilde{A}_j}\}_{j=1}^\ell$ that covers at least $K(1 - \nu_1(\vec{\lambda}) - \epsilon_0)$ elements of $[0, K-1]$. Because these collections are separated, there is a 1-1 correspondence between them and their complements. Hence, the number of such covers is less than

$$\psi(K, \lambda_j, \epsilon_0) = \sum_{j \leq (\nu_1 + \epsilon_0)K} \binom{K}{j} \quad (**)$$

Fix such a collection $\{\{I_i^j\}_{i \in \tilde{A}_j}\}_{j=1}^\ell$ and set

$$C = \{x \in E_K \mid \{I_i^j(x)\} = \{I_i^j\}\}.$$

From the construction we see that for every $1 \leq j \leq \ell$ we can cover B_j by no more than $2^{N_j(h_0 + \epsilon_0)}$ $(\mathcal{U}, [0, N_j - 1])$ -names, thus we can cover C by no more than $2^{N_j(h_0 + \epsilon_0)}$

(\mathcal{U}, I_i^j) -names. So the number of $(\mathcal{U}, [0, K - 1])$ -names, needed to cover C is at most

$$\begin{aligned} \prod_{j=1}^{\ell} (2^{N_j(h_0+\epsilon_0)})^{|\bar{A}_j|} \cdot M^{K(\nu_1+\epsilon_0)} &= 2^{(\sum_j N_j |\bar{A}_j|)(h_0+\epsilon_0)} \cdot M^{K(\nu_1+\epsilon_0)} \\ &\leq 2^{K(h_0+\epsilon_0)} \cdot M^{K(\nu_1+\epsilon_0)}. \end{aligned}$$

Finally we get from this and $(**)$ that

$$\mathcal{N}(\mathcal{U}_0^{K-1}, \rho_2) \leq \psi(K, \lambda_j, \epsilon_0) \cdot 2^{K(h_0+\epsilon_0)} \cdot M^{K(\nu_1+\epsilon_0)}$$

and so

$$\frac{1}{K} \log \mathcal{N}(\mathcal{U}_0^{K-1}, \rho_2) \leq \frac{1}{K} \log \psi(K, \lambda_j, \epsilon_0) + h_0 + \epsilon_0 + \nu_1 \log M + \epsilon_0 \log M.$$

If, in the construction of the towers, we choose δ small enough and N_1 large enough, we can ensure that $\lambda_j = N_j \mu(B_j) > \frac{1-\rho_1}{2}$ and thus $1 - \lambda_j < \frac{1+\rho_1}{2} \Rightarrow \nu_1 < (\frac{1+\rho_1}{2})^\ell$ and so, from $(*)$ we have that

$$\nu_1 \log M < \epsilon_0 \quad \nu_1 + \epsilon_0 \leq \frac{1}{2}$$

hence, from *lemma 2.3*

$$\psi(K, \lambda_j, \epsilon_0) \leq 2^{K \cdot H((\frac{1+\rho_1}{2})^\ell + \epsilon_0)}$$

hence

$$\begin{aligned} \frac{1}{K} \log \mathcal{N}(\mathcal{U}_0^{K-1}, \rho_2) &\leq h_0 + \epsilon_0(2 + \log M) + H((\frac{1+\rho_1}{2})^\ell + \epsilon_0) \Rightarrow \\ \limsup_K \frac{1}{K} \log \mathcal{N}(\mathcal{U}_0^{K-1}, \rho_2) &\leq h_0 + \epsilon_0(2 + \log M) + H((\frac{1+\rho_1}{2})^\ell + \epsilon_0) \end{aligned}$$

letting $\ell \rightarrow \infty$ and $\epsilon_0 \rightarrow 0$ we get

$$\limsup_K \frac{1}{K} \log \mathcal{N}(\mathcal{U}_0^{K-1}, \rho_2) \leq h_0$$

as desired. □

After proving *theorem 4.2*, we can define, for an ergodic m.t.d.s, (X, \mathcal{B}, μ, T) and a cover $\mathcal{U} = \{U_1 \dots U_M\}$ of X , a notion of measure theoretical entropy in the following way:

$$h_\mu^e(\mathcal{U}, T) = \lim_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) \quad \text{where } 0 < \epsilon < 1.$$

Often we omit T and write $h_\mu^e(\mathcal{U})$.

4.4. Theorem. $h_\mu^e(\mathcal{U}) = h_\mu^+(\mathcal{U})$

Proof. As before, if the system is periodic then $h_\mu^e(\mathcal{U}) = h_\mu^+(\mathcal{U}) = 0$. We assume, then, that the system is aperiodic. For every partition $\alpha \succeq \mathcal{U}$, $n \in \mathbb{N}$ and $0 < \epsilon < 1$, we have that $\mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) \leq \mathcal{N}(\alpha_0^{n-1}, \epsilon)$ and therefore

$$\begin{aligned} h_\mu^e(\mathcal{U}) &= \lim_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) \leq \lim_n \frac{1}{n} \log \mathcal{N}(\alpha_0^{n-1}, \epsilon) = h_\mu(\alpha) \\ &\Rightarrow h_\mu^e(\mathcal{U}) \leq h_\mu^+(\mathcal{U}) \end{aligned}$$

To prove the other inequality, we shall show that for a given $0 < \epsilon < \frac{1}{4}$ and $n \in \mathbb{N}$ we have:

$$h_\mu^+(\mathcal{U}) \leq \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) + \sqrt{\epsilon} \cdot \log M + H(\sqrt{\epsilon}). \quad (*)$$

Once we prove (*), we are done, for letting $n \rightarrow \infty$ we get $h_\mu^+(\mathcal{U}) \leq h_\mu^e(\mathcal{U}) + \sqrt{\epsilon} \cdot \log M + H(\sqrt{\epsilon})$ and now, letting $\epsilon \rightarrow 0$ we get $h_\mu^+(\mathcal{U}) \leq h_\mu^e(\mathcal{U})$ as desired.

Proof of (*): choose $\delta > 0$, such that $\epsilon + \delta < \frac{1}{4}$ and find a good base (β, \tilde{B}, B) for $(\mathcal{U}, n, \epsilon, \delta)$. (Now we take \tilde{B} to be a base for a strong Rohlin tower of height N and error $< \delta$ and not of height $N + 1$ as before). Set $N = \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon)$, so B is the union of N elements of $\beta|_{\tilde{B}}$. We index these elements by sequences $i_0 \dots i_{n-1}$, such that if $B_{i_0 \dots i_{n-1}}$ is one, then $T^j(B_{i_0 \dots i_{n-1}}) \subset U_{i_j}$, for every $0 \leq j \leq n - 1$. We have that $\mu(X \setminus \bigcup_0^{n-1} T^i(B)) \leq \epsilon + \delta$. Let $\hat{\alpha} = \{\hat{A}_1 \dots \hat{A}_M\}$ be the partition of

$$E = \bigcup_0^{n-1} T^i(B)$$

defined by

$$\hat{A}_m = \bigcup \{T^j(B_{i_0 \dots i_{n-1}}) \mid j \in [0, n-1], i_j = m\}.$$

Note that $\hat{A}_m \subset U_m$, for every $1 \leq m \leq M$. Extend $\hat{\alpha}$, to a partition, α , of X , refining \mathcal{U} , in some way. Set $\eta^2 = \epsilon + \delta$ and define for every $k > n$ $f_k(x) = \frac{1}{k} \sum_{i=0}^{k-1} \chi_E(T^i x)$. We have that $0 \leq f_k \leq 1$ and $\int f_k > 1 - \eta^2$, so if we will denote:

$$G_k = \{x \mid f_k(x) > 1 - \eta\}$$

then,

$$\eta \cdot \mu(G_k^c) \leq \int_{G_k^c} 1 - f_k \leq \int 1 - f_k \leq \eta^2$$

$$\Rightarrow \mu(G_k) \geq 1 - \eta.$$

We shall show that we can cover G_k , by "few" $(\alpha, [0, k-1])$ -names. Partition G_k according to the values of $0 \leq i \leq k - n$, such that $T^i x \in B$. Note that if $x \in G_k$ and $0 \leq i_1 < \dots < i_m \leq k - n$, are the times in which x visits B , then the collection $\{[i_j, i_j + n - 1]\}_{j=1}^m$ covers all but at most $\eta k + 2n$ elements of $[0, k-1]$. Because each element of this partition defines a collection of subintervals of $[0, k-1]$, of length n , that covers all but at most

$\eta k + 2n$, elements of $[0, k - 1]$, in a $1 - 1$ manner, we have that the number of elements in the partition of G_k is at most

$$\psi(k, n, \eta) = \sum_{j < (\eta + \frac{2n}{k})k} \binom{k}{j}$$

We fix an element C of this partition of G_k and want to estimate the number of $(\alpha, [0, k - 1])$ -names, needed to cover it. If $0 \leq i_1 < \dots < i_m \leq k - n$ are the times elements of C visit B , then we need at most N , $(\alpha, [i_j, i_j + n - 1])$ -names, to cover C . Because the size of $[0, k - 1] \setminus \bigcup_j [i_j, i_j + n - 1]$, is at most $\eta k + 2n$, we need at most $N^{\frac{k}{n}} \cdot M^{\eta k + 2n}$ $(\alpha, [0, k - 1])$ -names, to cover C . Finally, we have that we can cover G_k , by no more than:

$$\psi(k, n, \eta) \cdot N^{\frac{k}{n}} \cdot M^{\eta k + 2n}$$

$(\alpha, [0, k - 1])$ -names. Because $\mu(G_k) > 1 - \eta$, this means that:

$$\frac{1}{k} \log \mathcal{N}(\alpha_0^{k-1}, \eta) \leq \frac{1}{k} \log \psi(k, n, \eta) + \frac{1}{n} \log N + (\eta + \frac{2n}{k}) \log M.$$

Recall that once $(\eta + \frac{2n}{k}) < \frac{1}{2}$, we have $\psi(k, n, \eta) \leq 2^{k \cdot H(\eta + \frac{2n}{k})}$ and so

$$h_\mu(\alpha) = \lim \frac{1}{k} \log \mathcal{N}(\alpha_0^{k-1}, \eta) \leq \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) + \eta \cdot \log M + H(\eta)$$

so

$$h_\mu^+(\mathcal{U}) \leq \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) + \sqrt{\epsilon + \delta} \cdot \log M + H(\sqrt{\epsilon + \delta})$$

Letting $\delta \rightarrow 0$ we get

$$h_\mu^+(\mathcal{U}) \leq \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \epsilon) + \sqrt{\epsilon} \cdot \log M + H(\sqrt{\epsilon})$$

as desired. □

4.5. Theorem. $h_\mu^+(\mathcal{U}) = h_\mu^-(\mathcal{U})$

We already know that $h_\mu^+(\mathcal{U}) \geq h_\mu^-(\mathcal{U})$ (*Proposition 3.6*), so we only need to prove the other inequality. Before we turn to the proof, let us present some terminology and prove a combinatorial lemma.

Let Λ , be a finite alphabet of M letters, $k, n \in \mathbb{N}$ $k \gg n$, $0 < \delta < 1$ and $\omega = \omega_0^{k-1}$, a word of length k on Λ . (The symbol a_r^s stands for $a_r \dots a_s$). Denote $\Gamma = \Lambda^n$.

- An (n, k, δ) -packing is a pair $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$ where $0 \leq i_j \leq k - n$, $\gamma_j \in \Gamma$, $j = 0 \dots m - 1$, $i_j + n - 1 < i_{j+1}$ and $\frac{m-n}{k} > 1 - \delta$. (We think of an (n, k, δ) -packing as instructions to "almost" write a word of length k , we just fill it with the γ_j 's, where γ_j starts in the i_j letter and there will be no more than δk letters to add.)
- An (n, k, δ) -packing for ω , is an (n, k, δ) -packing, $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$, such that $\omega_{i_j}^{i_j+n-1} = \gamma_j$.

- if μ_1, μ_2 are probability distributions on Γ then

$$\|\mu_1 - \mu_2\| = \max_{\gamma} |\mu_1(\gamma) - \mu_2(\gamma)|.$$

- An (n, k, δ) -packing, $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$, induces a probability distribution on Γ , denoted by $P_{\mathcal{C}}$, by the formula $P_{\mathcal{C}}(\gamma) = \frac{1}{m} \#\{0 \leq j \leq m-1 \mid \gamma = \gamma_j\}$.
- If μ is a probability distribution on Γ and \mathcal{C} is an (n, k, δ) -packing, then we say that \mathcal{C} is (n, k, δ, μ) , if $\|\mu - P_{\mathcal{C}}\| < \delta$. We say that ω is (n, k, δ, μ) , if there is an (n, k, δ) -packing for ω , which is (n, k, δ, μ) .

4.6. Lemma. *If μ is a probability distribution on Γ , with "average entropy"*

$$h_0 = -\frac{1}{n} \sum_{\gamma \in \Gamma} \mu(\gamma) \log \mu(\gamma)$$

then there exists a positive function $\varphi(\delta)$, such that $\varphi(\delta) \rightarrow 0$ as $\delta \rightarrow 0$ and such that if $0 < \delta < \frac{1}{2}$, then for any $k > n$, the number of words $\omega \in \Lambda^k$, which are (n, k, δ, μ) , is at most $2^{k(h_0 + \varphi(\delta))}$.

Proof. Fix $k > n$. We want to estimate the number of words $\omega = \omega_0^{k-1} \in \Lambda^k$, that are (n, k, δ, μ) . For every such word, ω , we can choose an (n, k, δ) -packing, $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$ which is (n, k, δ, μ) . In this way we define a map

$$\pi : \{\omega \in \Lambda^k \mid \omega \text{ is } (n, k, \delta, \mu)\} \rightarrow \{\mathcal{C} \mid \mathcal{C} \text{ is an } (n, k, \delta, \mu) - \text{packing}\}$$

If $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$, is an (n, k, δ) -packing, then $\frac{n \cdot m}{k} > 1 - \delta$. This means that $|\pi^{-1}(\mathcal{C})| \leq |\Lambda|^{\delta k} = M^{\delta k}$. So we have that

$$\#\{\omega \in \Lambda^k \mid \omega \text{ is } (n, k, \delta, \mu)\} \leq M^{\delta k} \#\{\mathcal{C} \mid \mathcal{C} \text{ is an } (n, k, \delta, \mu) - \text{packing}\}.$$

Let us now estimate the number of (n, k, δ, μ) -packings, $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$:

The number of sequences, i_0^{m-1} , such that $0 \leq i_j \leq k-n$, $i_j + n-1 < i_{j+1}$ and $\frac{m \cdot n}{k} > 1 - \delta$ is at most $\sum_{j < \delta k} \binom{k}{j}$. From lemma 2.3 we know that for $\delta < \frac{1}{2}$, this sums to something $\leq 2^{H(\delta)k}$.

Fix such a sequence i_0^{m-1} . Let us now estimate the number of sequences, γ_0^{m-1} , such that the (n, k, δ) -packing, $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$, is (n, k, δ, μ) .

Denote $\nu = \otimes_1^m \mu$, the product measure on Γ^m . If $\gamma_0^{m-1} \in \Gamma^m$, then

$$\begin{aligned} \nu(\gamma_0^{m-1}) &= \prod_{\gamma \in \Gamma} \mu(\gamma)^{\#\{0 \leq j \leq m-1 \mid \gamma = \gamma_j\}} = 2^{\sum_{\{\gamma \mid \mu(\gamma) \neq 0\}} \#\{0 \leq j \leq m-1 \mid \gamma = \gamma_j\} \cdot \log \mu(\gamma)} \\ &= 2^{m \sum_{\{\gamma \mid \mu(\gamma) \neq 0\}} \frac{1}{m} \#\{0 \leq j \leq m-1 \mid \gamma = \gamma_j\} \cdot \log \mu(\gamma)}. \end{aligned}$$

Now, the function $f : \{(x_{\gamma})_{\gamma \in \Gamma} \in \mathbb{R}^{\Gamma} \mid \sum x_{\gamma} = 1\} \rightarrow \mathbb{R}$, defined by

$$f(\vec{x}_{\gamma}) = \sum_{\{\gamma \mid \mu(\gamma) \neq 0\}} x_{\gamma} \cdot \log \mu(\gamma)$$

is continuous and so there is a positive function $\psi(\delta)$, such that $\psi(\delta) \rightarrow 0$ as $\delta \rightarrow 0$ and if $\max_{\gamma} |x_{\gamma} - \mu(\gamma)| < \delta$, then $|f(\vec{x}_{\gamma}) - f(\mu(\vec{\gamma}))| < \psi(\delta)$ (note that ψ depends only on n , μ). So if $\gamma_0^{m-1} \in \Gamma^m$ is such that $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$, is a (n, k, δ, μ) -packing, it follows that

$$\begin{aligned}\nu(\gamma_0^{m-1}) &= 2^m \sum_{\{\gamma \mid \mu(\gamma) \neq 0\}} \frac{1}{m} \# \{0 \leq j \leq m-1 \mid \gamma = \gamma_j\} \cdot \log \mu(\gamma) \\ &\geq 2^m \left(\sum_{\{\gamma \mid \mu(\gamma) \neq 0\}} \mu(\gamma) \log \mu(\gamma) - \psi(\delta) \right) \geq 2^{k(-h_0 - \frac{\psi(\delta)}{n})}\end{aligned}$$

Where the last inequality follows from the fact that $m < \frac{k}{n}$ and the definition of h_0 . We conclude that an upper bound for the number of such sequences γ_0^{m-1} is $2^{k(h_0 + \frac{\psi(\delta)}{n})}$. If we collect these estimations, we get to the conclusion that for $0 < \delta < \frac{1}{2}$

$$\#\{\omega \in \Lambda^k \mid \omega \text{ is } (n, k, \delta, \mu)\} \leq M^{\delta k} \cdot 2^{H(\delta)k} \cdot 2^{k(h_0 + \frac{\psi(\delta)}{n})} \leq 2^{k(h_0 + \frac{\psi(\delta)}{n} + H(\delta) + \delta \cdot \log M)}$$

so $\varphi(\delta) = \frac{\psi(\delta)}{n} + H(\delta) + \delta \cdot \log M$ is our desired function. \square

Proof. (of theorem 4.5): We want to show that for an ergodic system (X, \mathcal{B}, μ, T) and a cover $\mathcal{U} = \{U_1 \dots U_M\}$ of X , we have $h_{\mu}^+(\mathcal{U}) \leq h_{\mu}^-(\mathcal{U})$. As before, if the system is periodic, then, from the ergodicity, it must be a cyclic permutation on a finite set of atoms. Therefore $h_{\mu}^+(\mathcal{U}) = h_{\mu}^-(\mathcal{U}) = 0$. In the aperiodic case we can use the Strong Rohlin Lemma.

Let $\epsilon > 0$. We shall show that $h_{\mu}^+(\mathcal{U}) \leq h_{\mu}^-(\mathcal{U}) + 2\epsilon$. From the definition of $h_{\mu}^-(\mathcal{U})$, we can find $n \in \mathbb{N}$ and a partition $\beta \succeq \mathcal{U}_0^{n-1}$, such that $\frac{1}{n}H_{\mu}(\beta) \leq h_{\mu}^-(\mathcal{U}) + \epsilon$. As $\beta \succeq \mathcal{U}_0^{n-1}$, we can index the elements of β , by sequences $i_0^{n-1} = i_0 \dots i_{n-1}$, such that if $\tilde{B}_{i_0^{n-1}}$, is one, then $T^j \tilde{B}_{i_0^{n-1}} \subset U_{i_j}$, $j = 0 \dots n-1$. We can assume that each sequence, i_0^{n-1} , corresponds to, at most one element of β , for otherwise, we could unite these elements and get a coarser partition β' , still refining \mathcal{U}_0^{n-1} , such that $\frac{1}{n}H_{\mu}(\beta') \leq \frac{1}{n}H_{\mu}(\beta) \leq h_{\mu}^-(\mathcal{U}) + \epsilon$. Set $\Gamma = \{1 \dots M\}^n$. So the elements of β are indexed by Γ . (if $\gamma \in \Gamma$, does not correspond to an element of β , in the above way, we set $\tilde{B}_{\gamma} = \emptyset$). In this way, the partition β , defines a probability distribution, ν , on Γ , defined by $\nu(\gamma) = \mu(\tilde{B}_{\gamma})$ and we have that $h_0 = \frac{1}{n}H_{\mu}(\beta)$, is the "average entropy" (see Lemma 4.6) of ν .

Choose $\delta > 0$ (in a manner specified later) and let F , be a base for a strong Rohlin tower (with respect to β) of height n and error $\leq \delta^2$. Denote the atoms of $\beta|_F$ by B_{γ} , $\gamma \in \Gamma$, (where $B_{\gamma} = \tilde{B}_{\gamma} \cap F$), and define a partition $\tilde{\alpha} = \{\tilde{A}_1 \dots \tilde{A}_M\}$ of $E = \bigcup_0^{n-1} T^j F$, by $\tilde{A}_m = \bigcup \{T^j B_{i_0^{n-1}} \mid j \in \{0 \dots n-1\}, i_j = m\}$. Note that $\tilde{A}_m \subset U_m$. Extend $\tilde{\alpha}$, to a partition α of X refining \mathcal{U} , in some way. The set of indices of elements of α , Λ (the alphabet in which α -names are written) contains $\{1 \dots M\}$ and we can always build α , such that $|\Lambda| \leq 2M$. We slightly abuse our notation and denote $\Gamma = \Lambda^n$. In this way, ν is still a probability distribution on Γ .

Claim: If δ , is small enough, then $h_{\mu}(\alpha) \leq h_0 + \epsilon$.

Once we prove this claim, we are done, because then

$$h_{\mu}^+(\mathcal{U}) \leq h_{\mu}(\alpha) \leq h_0 + \epsilon \leq h_{\mu}^-(\mathcal{U}) + 2\epsilon.$$

Proof of claim: For $k \gg n$, we look at the function $f_k(x) = \frac{1}{k} \sum_0^{k-1} \chi_E(T^j x)$. We have that $0 \leq f_k \leq 1$ and $\int f_k > 1 - \delta^2$. Therefore

$$\begin{aligned} \delta \cdot \mu(\{x | 1 - f_k(x) > 1 - \delta\}) &\leq \int_{\{x | 1 - f_k(x) > 1 - \delta\}} 1 - f_k \leq \int 1 - f_k \leq \delta^2 \\ &\Rightarrow \mu(\{x | f_k(x) \geq 1 - \delta\}) \geq 1 - \delta. \end{aligned}$$

Denote, $G_1^k = \{x | f_k(x) \geq 1 - \delta\}$. For $x \in G_1^k$, there are at most δk times $0 \leq i \leq k-1$, such that $T^i x \notin E$. Define

$$G_2^k = \{x | \left| \frac{1}{k} \sum_0^{k-n} \chi_A(T^i x) - \mu(A) \right| < \delta, A \in \beta|_F \cup \{F\}\}.$$

Let us see what can we say about the $(\alpha, [0, k-1])$ -name of an element, x , of $G_1^k \cap G_2^k$. Fix such an x and denote by $i_0 < \dots < i_{m-1}$, the times between 0 to $k-n$ in which x visits F . We have that $0 \leq i_j \leq k-n$, $i_j + n - 1 < i_{j+1}$ (that is because the height of the tower is n). Except for at most $2n$ times (n at the beginning and n at the end), x visits E , exactly in the times $i_j \dots i_j + n - 1$, $j = 1 \dots m-1$. Therefore, we must have

$$n \cdot m \geq (1 - \delta)k - 2n \Rightarrow \frac{n \cdot m}{k} \geq 1 - (\delta + \frac{2n}{k})$$

Denote the $(\alpha, [0, k-1])$ -name of x by $\omega = \omega_0^{k-1}$ ($\omega_i \in \Lambda$), and $\gamma_j = \omega_{i_j} \dots \omega_{i_j+n-1} \in \Gamma$, $j = 0 \dots m-1$. We have that $\mathcal{C} = (i_0^{m-1}, \gamma_0^{m-1})$ is an $(n, k, \delta + \frac{2n}{k})$ -packing for ω . Let us now see, what can we say about the distribution, $P_{\mathcal{C}}$, this packing induces on Γ .

For $0 \leq r \leq k-n$, we have that $T^r x \in B_{\gamma}$ if and only if, there is a $0 \leq j \leq m-1$, such that $r = i_j$ and $\gamma = \gamma_j$. Therefore, because $x \in G_2^k$

- $\forall \gamma \in \Gamma \quad \left| \frac{1}{k} \# \{0 \leq j \leq m-1 | \gamma = \gamma_j\} - \mu(B_{\gamma}) \right| < \delta.$
- $\left| \frac{m}{k} - \mu(F) \right| < \delta.$

Note that $\mu(F) > \frac{1-\delta}{n}$, so if δ is sufficiently small, we can guarantee that $\left| \frac{k}{m} - \frac{1}{\mu(F)} \right|$ would be arbitrarily small and in turn we can guarantee that for every $\gamma \in \Gamma$

$$\left| \frac{k}{m} \cdot \frac{1}{k} \# \{0 \leq j \leq m-1 | \gamma = \gamma_j\} - \frac{\mu(B_{\gamma})}{\mu(F)} \right| = |P_{\mathcal{C}}(\gamma) - \nu(\gamma)|$$

would be arbitrarily small. This is to say that $\|P_{\mathcal{C}} - \nu\|$ is arbitrarily small. We see that there is a positive function $\psi(\delta)$, independent of k , such that $\psi(\delta) \rightarrow 0$ as $\delta \rightarrow 0$ and such that, if $x \in G_1^k \cap G_2^k$ and ω is its $(\alpha, [0, k-1])$ -name, then ω is $(n, k, \psi(\delta) + \frac{2n}{k}, \nu)$.

Remember the function φ , from lemma 4.6. There is an $\eta_0 > 0$, such that for every $0 < \eta < \eta_0$ $\varphi(\eta) < \epsilon$. Choose k to be large enough so that $\frac{2n}{k} < \frac{\eta_0}{2}$ and the error, δ , of the tower to be so small, such that $\psi(\delta) < \frac{\eta_0}{2}$, and conclude, from lemma 4.6, that the number of $(\alpha, [0, k-1])$ -names of elements of $G_1^k \cap G_2^k$ is at most $2^{k(h_0+\epsilon)}$. From the ergodicity, we know that for large enough k , $\mu(G_1^k \cap G_2^k) > 1 - 2\delta$, so we have

$$h_{\mu}(\alpha) = \lim \frac{1}{k} \log \mathcal{N}(\alpha_0^{k-1}, 2\delta) \leq h_0 + \epsilon.$$

as desired.

□

Remarks:

- If (X, T) , is totally ergodic, i.e (X, T^n) , is ergodic for every $n \in \mathbb{N}$, then we can look at expressions like $h_\mu^e(\mathcal{U}_0^{n-1}, T^n)$. It follows from the definition that $h_\mu^e(\mathcal{U}, T) = \frac{1}{n}h_\mu^e(\mathcal{U}_0^{n-1}, T^n)$. This enables us to prove the last theorem without any hard work done. We know from *theorem 4.4*, that $h_\mu^e(\mathcal{U}, T) = h_\mu^+(\mathcal{U}, T)$ and therefore $h_\mu^+(\mathcal{U}, T) = \frac{1}{n}h_\mu^+(\mathcal{U}_0^{n-1}, T^n)$. But then, *proposition 3.6* (which is elementary), gives: $h_\mu^-(\mathcal{U}, T) = \lim \frac{1}{n}h_\mu^+(\mathcal{U}_0^{n-1}, T^n) = h_\mu^+(\mathcal{U}, T)$ and this gives the desired result.
- The definitions of $h_\mu^+(\mathcal{U}), h_\mu^-(\mathcal{U})$, were introduced in [R] and discussed also in [Ye], [HMRY]. There, a proof of their equality was given only in the case where (X, T) , is a t.d.s, and \mathcal{U} is an open cover. The proof was based on a reduction to a uniquely ergodic case and then a use of a variational inequality, proved in [GW].
- The definition of $h_\mu^e(\mathcal{U})$ is new. This definition helps us to prove directly a slight generalization of the variational inequality ,proved in [GW] and mentioned above, to the non-topological case. (*Theorem 6.1*).
- The proofs of theorems 4.2, 4.4, 4.5 and lemma 4.6 are based on ideas of B.Weiss and E.Glasner

5. ERGODIC DECOMPOSITION FOR h_μ^+, h_μ^-

5.1. Theorem. (*Proposition 5 in [HMRY]*): Let $\mathcal{U} = \{U_1 \dots U_M\}$, be a cover of X , and $\mu = \int \mu_x d\mu(x)$, the ergodic decomposition of μ with respect to T . Then

$$h_\mu^+(\mathcal{U}, T) = \int h_{\mu_x}^+(\mathcal{U}, T) d\mu(x) \quad h_\mu^-(\mathcal{U}, T) = \int h_{\mu_x}^-(\mathcal{U}, T) d\mu(x)$$

5.2. Corollary. $h_\mu^+(\mathcal{U}) = h_\mu^-(\mathcal{U})$

Proof. It follows immediately from the above and the ergodic case (*Theorem 4.5*) □

From now on we will denote the number $h_\mu^+(\mathcal{U}, T) = h_\mu^-(\mathcal{U}, T) (= h_\mu^e(\mathcal{U}, T)$ in the ergodic case), simply by $h_\mu(\mathcal{U}, T)$ or $h_\mu(\mathcal{U})$ or $h(\mathcal{U})$, when no ambiguity can occur.

6. VARIATIONAL RELATIONS

As always, let $\mathcal{U} = \{U_1 \dots U_M\}$, be a cover of the m.t.d.s (X, \mathcal{B}, μ, T) . We can define the "combinatorial entropy" of \mathcal{U} as

$$h_c(\mathcal{U}, T) = \lim_n \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1})$$

where, $\mathcal{N}(\mathcal{V})$, is the minimum number of elements of \mathcal{V} , needed to cover the whole space. Note that the sequence $\log \mathcal{N}(\mathcal{U}_0^{n-1})$, is sub-additive, hence the limit exists. If (X, T) is a t.d.s and \mathcal{U} is an open cover then we denote $h_{top}(\mathcal{U}, T) = h_c(\mathcal{U}, T)$.

The next theorem was proved in [GW] for topological dynamical systems and measurable covers. We give here a simple proof for the non topological case that uses the definition of $h_\mu^e(\mathcal{U})$.

6.1. Theorem. $h_\mu(\mathcal{U}) \leq h_c(\mathcal{U})$.

Proof. First, if the system is ergodic, then $h_\mu(\mathcal{U}) = \lim \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}, \frac{1}{2})$ and as $\mathcal{N}(\mathcal{U}_0^{n-1}, \frac{1}{2}) \leq \mathcal{N}(\mathcal{U}_0^{n-1})$, we have

$$h_\mu(\mathcal{U}) \leq \lim \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}) = h_{top}(\mathcal{U})$$

as desired. In the non ergodic case, let $\mu = \int \mu_x d\mu(x)$, be the ergodic decomposition of μ . By theorem 5.1, $h_\mu(\mathcal{U}) = \int h_{\mu_x}(\mathcal{U}) d\mu(x)$, so from the first part we see that $h_\mu(\mathcal{U}) \leq h_c(\mathcal{U})$. \square

Remark: Another simple proof of the above, uses the definition of $h_\mu^-(\mathcal{U})$:

$$\begin{aligned} H_\mu(\mathcal{U}_0^{n-1}) &= \inf_{\alpha \succeq \mathcal{U}_0^{n-1}} H_\mu(\alpha) \leq \inf_{\alpha \succeq \mathcal{U}_0^{n-1}} \log |\alpha| \leq \log \mathcal{N}(\mathcal{U}_0^{n-1}) \\ &\Rightarrow h_\mu(\mathcal{U}) = \lim \frac{1}{n} H_\mu(\mathcal{U}_0^{n-1}) \leq \lim \frac{1}{n} \log \mathcal{N}(\mathcal{U}_0^{n-1}) = h_c(\mathcal{U}). \end{aligned}$$

From this stage, until the end of this paper we assume that (X, T) , is a t.d.s. We denote by $\mathcal{M}_T(X)$, the set of T -invariant probability measures on X and by $\mathcal{M}_T^e(X)$, the set of ergodic ones. Also \mathcal{C}_X^o , will denote the set of finite open covers of X .

In [BGH], the following theorem was proved:

6.2. Theorem. (*Theorem 1 in [BGH]*): If $\mathcal{U} \in \mathcal{C}_X^o$, then there exists $\mu \in \mathcal{M}_T(X)$, such that $h_\mu(\mathcal{U}) \geq h_{top}(\mathcal{U})$.

In light of theorem 6.1 we have that for every $\mathcal{U} \in \mathcal{C}_X^o$, one can find a measure $\mu \in \mathcal{M}_T(X)$, such that $h_\mu(\mathcal{U}) = h_{top}(\mathcal{U})$. In fact theorem 7 in [HMRY] now becomes:

6.3. Corollary. for every $\mathcal{U} \in \mathcal{C}_X^o$, one can find a measure $\mu \in \mathcal{M}_T^e(X)$, such that $h_\mu(\mathcal{U}) = h_{top}(\mathcal{U})$.

Proof. Choose $\mu \in \mathcal{M}_T(X)$, such that $h_\mu(\mathcal{U}) = h_{top}(\mathcal{U})$, and let $\mu = \int \mu_x d\mu(x)$, be its ergodic decomposition. We know that

$$h_{top}(\mathcal{U}) = h_\mu(\mathcal{U}) = \int h_{\mu_x}(\mathcal{U}) d\mu(x)$$

and that $h_{\mu_x}(\mathcal{U}) \leq h_{top}(\mathcal{U})$. So we must have $h_{\mu_x}(\mathcal{U}) = h_{top}(\mathcal{U})$ for $[\mu]$ a.e x . \square

We conclude from the above, the classical variational principle:
First we state a technical lemma, taken from [Ye].

6.4. Lemma. For any $\epsilon > 0$, $\mu \in \mathcal{M}_T(X)$ and $\alpha = \{A_1 \dots A_M\} \in \mathcal{P}_X$, there exists an open cover $\mathcal{U} \in \mathcal{C}_X^o$, such that for every partition $\beta \succeq \mathcal{U}$ one has $H_\mu(\alpha|\beta) < \epsilon$.

6.5. Theorem. (*The Variational Principle*):

(a) For every $\mu \in \mathcal{M}_T(X)$, $h_\mu(T) \leq h_{top}(T)$.

$$(b) \sup_{\mu \in \mathcal{M}_T^e(X)} h_\mu(T) = h_{top}(T).$$

Proof. To prove (a), we first show that for each $\mu \in \mathcal{M}_T(X)$, $h_\mu(T) = \sup_{\mathcal{U} \in \mathcal{C}_X^o} h_\mu(\mathcal{U}, T)$. If this is done, then from *theorem 6.1*, we get

$$h_\mu(T) \leq \sup_{\mathcal{U} \in \mathcal{C}_X^o} h_{top}(\mathcal{U}, T) = h_{top}(T).$$

It follows from the definition, that for any cover \mathcal{U} of X , we have $h_\mu(\mathcal{U}, T) \leq h_\mu(T)$, so one inequality is clear. For the other inequality, fix a partition, $\alpha = \{A_1 \dots A_M\}$, of X and $\epsilon > 0$. We need to find an open cover, \mathcal{U} , of X , such that $h_\mu(\alpha, T) \leq h_\mu(\mathcal{U}, T) + \epsilon$. By the preceding lemma and from the fact that for any $\beta \in \mathcal{P}_X$ one has $h_\mu(\alpha) \leq h_\mu(\beta) + H(\alpha|\beta)$ we have $\mathcal{U} \in \mathcal{C}_X^o$, such that

$$h_\mu(\mathcal{U}, T) = \inf_{\beta \succeq \mathcal{U}} h_\mu(\beta, T) \geq \inf_{\beta \succeq \mathcal{U}} (h_\mu(\alpha, T) - H_\mu(\alpha|\beta)) \geq h_\mu(\alpha, T) - \epsilon.$$

To prove (b), note that from (6.3) we know that for any $\mathcal{U} \in \mathcal{C}_X^o$, we can find $\mu \in \mathcal{M}_T^e(X)$, such that $h_\mu(\mathcal{U}, T) = h_{top}(\mathcal{U}, T)$. This gives us

$$\sup_{\mu \in \mathcal{M}_T^e(X)} h_\mu(T) \geq h_{top}(\mathcal{U}, T) \Rightarrow \sup_{\mu \in \mathcal{M}_T^e(X)} h_\mu(T) \geq \sup_{\mathcal{U} \in \mathcal{C}_X^o} h_{top}(\mathcal{U}, T) = h_{top}(T).$$

Together with (a), we get equality, which is (b). \square

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